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The Potential Role of New Technology for Enhanced Safety and Performance of Nuclear Power Plants Through Improved Service Maintenance

by

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The Potential Role of New Technology for Enhanced Safety and Performance of Nuclear Power Plants Through Improved Service Maintenance

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ABSTRACT

Refinements in the safety and performance of nuclear power plants must be made to maintain public confidence and ensure competitiveness with other power sources. The aircraft industry, US Navy, and other programs have proven many advanced service maintenance methods that may improve commercial nuclear plants.

This thesis is concerned with how new technologies in sensing and monitoring can be used to reduce the potential for hardware failures. The specific components with the greatest impacts upon safety and performance were determined using historical data from the experience of the nuclear industry. Failure modes associated with selected components are used to indicate the most important monitoring needs and these requirements help focus a technology survey for potential improvements. The thesis concludes with a discussion of possible applications which may enhance monitoring needs. Proposals for focusing future research to further develop appropriate technologies are presented.

Nuclear facility managers are provided a means to self-analyze the status of onsite efforts to improve vital safety and performance related equipment in this thesis. Many of the monitoring needs and potential improvements indicated have general application to most plants. The process discussed in this report can be used to further tailor technology to plant specific needs.

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Chapter 1

Introduction

1.1 Foreword

Improvements of safety and performance in nuclear facilities are important to the future of the world's nuclear power programs. Methods of enhancing safety are vital because of tenuous public acceptance of nuclear power following past accidents. Improved plant performance is critical for the economic feasibility of future nuclear power operations.

An international cooperative program, created at the Massachusetts Institute of Technology (MIT), is investigating ways to improve nuclear power plants safety and operation. This program will investigate methods to identify practices, procedures, policies, and organizational structures that promote safe and efficient operation of the plants. The program has no international boundaries which allows nuclear power programs worldwide to benefit (H-1).

This research project contributes to one of the MIT program objectives by seeking ways to improve component reliability and therefore overall plant performance and safety through application of technology. Only the most important components with respect to safety and performance in Pressurized Water Reactors (PWRs) are considered. Several designs were evaluated to determine the most representative important components for the entire industry. A survey of promising technologies was conducted and possible

improvements to selected components are presented.

1.2 Background

Several industries have the shown benefits of using technology to improve performance and monitoring of components. These industries have used relatively small initial investments in technical improvements and monitoring equipment to vastly improve equipment reliability and operation. Two examples of successful application of technology for equipment improvement are the commercial airline industry and the US Navy's submarine program.

In the early 1960's, the airline industry used technical advances to improve its maintenance programs. Until this time, maintenance had been a learned craft with little analytical methods. As equipment became more complex, maintenance cost increased and it became difficult to maintain component reliability. Through the application of advanced technology, maintenance costs were reduced, equipment reliability was improved, and aircraft safety was enhanced (R-1). Fewer aircraft had to be taken off-line for corrective maintenance, improving plane availability, and fewer planes had to be purchased to maintain a given flight schedule.

Component performance onboard US Navy nuclear powered submarines has improved through refined monitoring and information management. Reforms have increased the average time between normal submarine overhauls by over 100 per cent, saving millions of dollars annually and the program cost is

a small fraction of the savings realized. In addition, submarine safety has been greatly improved offering further motivation for enhanced maintenance practices (S-1).

The airline and submarine improved maintenance programs have benefited from component enhancements. Similar methods and improved technologies can further improve areas of plant safety and performance for the commercial nuclear power industry.

Recent environmental protection interests have renewed public concerns about nuclear power plant safety. A review of power plant maintenance and surveillance activities by the Nuclear Regulatory Commission (NRC) has intensified the focus of attention on nuclear safety (N-1). Component reliability in a complex nuclear power plant has always been a concern and maintenance methods can be improved. Therefore, application of technology for improved service maintenance and component reliability could have a very positive effect on the safety image of the nuclear power industry.

Due to increased maintenance and operating cost at nuclear facilities, coal burning power plants provide power as much as 10 per cent cheaper than nuclear plants, highlighting the importance of applying technology to improve nuclear power plant performance (S-2). Technology may reduce cost of testing and lower maintenance shutdown time and frequency. Monitoring of component conditions using current technology can identify when maintenance is required based on data collected during normal operations. Shorter shutdown periods can

occur due to more efficient maintenance using technology. These examples of performance improvements show how benefits of technology can appear as more predictive and less costly maintenance.

In order to focus new technology effectively, a study of the most important contributors to plant safety and lost capacity is vital. Using probabilistic risk assessments (PRAs), accident precursor reports, industry maintenance data bases, and other industry methods to carry out such a study, this thesis determines the most important components affecting safety and performance.

A survey of industry personnel and literature was conducted to identify technologies that might improve the important components selected by methods discussed above. In several cases, technology could be directly applied. In other cases, further technical improvements are suggested, requiring research on additional component advancements.

Recommendations of this thesis could potentially improve important nuclear power components through revised application of technology. Future research focus for additional improvements is also indicated. By continuing to improve important components with respect to safety and performance, public opinion and economic performance of nuclear power could be greatly improved.

1.3 Research Approach and Organization of the Report

Table 1.3-1 illustrates the approach used in this thesis to identify how technology can improve nuclear power plant safety and performance.

Table 1.3-1

Potential Safety and Performance Related Improvements Process

1. Determine basis for determining importance (impact on CDF[1] or CFL[2])
2. Determine important events through industry survey
3. Identify important components (using #2 data)
4. Establish failure mode categories from the important components (using #3 data)
5. Develop monitoring needs from the failure modes (using #4 data)
6. Survey technology for improvements to the monitoring needs (focus on #5 needs)
7. Apply technology to the monitoring needs
8. Identify where further research is required

Each step of this process provides information for the next step. Flexibility is required due to frequently changing data. Emendations in nuclear power plant policies, designs and regulations may affect the selection of important components which impact the technology surveyed. Conversely, as new technologies develop, their application to power plant needs should be amended.

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1 CDF = core damage frequency discussed in Chapter 2

2 CFL = capacity factor losses discussed in Chapter 2

Chapters and sections in this thesis outline the research approach. Chapter 2 discusses how important contributors to power plant safety and performance were identified. Methods used to determine which components are most important are discussed along with summaries of important components for safety and performance.

Failure or degradation modes of components are used to identify monitoring needs in Chapter 3. Using these needs as a focus, the search for technologies which offer potential improvements can be concentrated in the most important areas.

Chapter 4 presents a survey of technological developments. Only technologies that have the greatest potential for improving important components are discussed. Each technology category is explained with some current applications proposed.

Chapter 5 discusses potential application of new technology to improve important components. Future research recommendations are made when important components can not be improved by current technology.

Appendix A contains definitions of terms and abbreviations. Appendix B contains discussions of the common safety and performance related events.

Chapter Two

Important Components

2.1 Introduction

Components with the greatest impact on, or importance with respect to, power plant safety or performance are identified in this chapter. Potential impact on core damage frequency (CDF), a measure of the probability that core damage will occur as the result of an event (N-2), was used to select safety components. Component influence on capacity factor losses (CFL) was used to select important performance related components. CFL measures the amount of energy lost due to an event compared to the calculated maximum energy a plant may produce at full power (S-5). By selecting the most important components, monitoring needs of the nuclear power industry can be identified.

Components were selected using results of several industry studies to identify power plant events with the greatest safety and performance effects. To determine the most significant component contributors for each event, studies were analyzed for general industry trends, or for impacts on specific power plant designs. As indicated in Chapter One, study reviews were limited to PWR designs with an effort made to select components that best represent the entire PWR community. In an effort to remove biases introduced by a single study or unimportant issues that pertain to limited power plant designs, several studies were evaluated in each category of safety or performance. A description of each event is contained in Appendix B.

Probabilistic risk assessments (PRAs) for specific plants, a survey of several PRAs, failure mode analysis studies, nuclear operating performance reviews and performance studies are some examples of reports used to determine which components have the greatest impact. Most of these studies involve statistical, logic or performance methods that yield quantitative results. Information was used to select important events for each study, allowing comparison of events within a study based on relative importance. Within each category of safety or performance, inputs from each study were compared and a final list of important events derived. Only events which were repeated between studies or which offered a significant impact were included in the final composite list for each category.

Events were not ranked within the final composite important event list. To obtain a relative ranking from different studies, events would have to be analyzed on the same basis. However, studies with separate, relative ranking within each study are difficult to correlate to other reports. For this reason, important events from different studies are treated equally. Since this thesis is interested in pursuing improvements to all important components, there was no need to prioritize the events.

Once vital events were selected, associated components could then be identified by using industry studies to provide insight into the contributors for each event. Only significant contributors are included on the composite list of important components.

2.2 Safety Related Components

Components with the greatest impact on power plant safety are discussed in this section. A brief background discussion of each study reviewed during the selection process is included along with methods used to merge inputs from each report. A listing of the most important events and a discussion on why these events were selected is provided. The section concludes with a listing of important safety-related components.

There are three levels of evaluation for potential risk associated with a nuclear power plant. Accident probabilities that may result in core damage are determined by "level one" evaluations. The possibility of these accidents releasing radioactivity to the public are evaluated by "Level two". "Level three" studies combine release probabilities and their consequences to obtain the overall public health risk (L-1). Most studies evaluated by this thesis are level one studies; however, some contain level two and three evaluations.

2.2.1 Safety Related Component Selection Process

Methods used to determine important safety related components for a nuclear power plant are discussed in this subsection. Components were selected based on their impact on the most significant power plant events that have the greatest potential for increasing core damage frequency (CDF). Several industry studies evaluate these issues and were used in this thesis.

These studies investigate potential failure possibilities of components that contribute to an event. Many of the analytical methods reduce to computer

codes making evaluations quicker and more accurate. This allows a detailed analysis of the potential for an event to occur in future plant operations. Events with the greatest potential for occurrence are highlighted in this process.

The following studies were reviewed to determine safety related components:

(1) Analysis of Severe Core Damage Potential Nureg-1150 and Nureg/CR 4550 (N-3,4,5,6),

(2) Status reports on precursors to potential severe core damage accidents (N-7,8, M-1),

(3) Plant Probabilistic Risk Assessments (PRAs) (C-1, E-1, P-1, P-2)

(4) Two reports summarizing the lessons learned from 21 nuclear power plant PRAs, 14 of which are PWRs (G-1,2).

A severe accident risks assessment report (Nureg 1150), issued by the Nuclear Regulatory Commission (NRC) in June of 1989, summarized the Analysis of Core Damage Reports (Nureg/CR-4550) for five light water reactors (LWR) along with other inputs. Nureg 4550 performed an evaluation that was a near state-of-the-art, level one PRA, as well as, level two and level three evaluations. These studies identified potential significant system failures for the five plants analyzed. Inputs allowed the Nureg 1150 report to provide an assessment of risks associated with plant designs and operational practices (N-2,3,4,5,6).

Three of five plants analyzed by Nureg 1150 are PWR plants and only this data was used in this research. Additionally, external and offsite events and consequences analyzed by Nureg 1150 were not used in this thesis in order to maintain a focus on important internal event data.

The second report listed above reviews Licensee Event Reports (LERs) and other operational plant data to identify when precursors to potential core damage, called Accident Sequence Precursors (ASP), have occurred. ASP events impact safety system unavailability or mitigating system degradation affecting core damage frequency. These reports determine the frequency of occurrence of ASPs and those occurring at higher frequencies highlight more important events which can be used to prioritize event safety impact. In addition, the ASP reports contain information indicating what lead to the precursor's occurrence (N-7,8, M-1) which is helpful in identifying key equipment and failure modes . This assists the process of determining which components are the greatest contributors to each event.

Specific plant PRA's show structured analysis methods accounting for all possible scenarios that could lead to core damage for a specific plant. Probabilities and statistical biasing factors determine which sequences are most significant and indicate the dominant component in each damage sequence. In this fashion, a ranking of events in order of impact on core damage potential can be obtained (C-1, E-1, P-3,4). Four PWR plant PRA reports were reviewed and important components from these reports were incorporated into the final composite important safety component list .

Lessons learned from 21 PRA's, 14 of which were from PWR plants, were analyzed by Pickard, Lowe and Garrick, Inc (PLG). Data from these studies was used to further enhance analysis of power plant safety sensitive components. Although many of the PRA's identify plant specific components that apply to only one or very few plant designs, some trends were identified between studies and may indicate industry wide components that impact safety. The PLG work highlights the significance of PRAs in determining sequences that have the greatest impact on safety, outlining how things go wrong and in what fashion. In addition, component changes, such as improved performance due to better service maintenance, can be quickly evaluated (G-1,2).

All of the studies provide an overview of risks associated with plant designs, operational practices, or potential component performance, allowing principal contributors to core damage frequency to be identified in a quantitative fashion. Relative importance of an event can be evaluated within a study. Each study determined which events were the most significant. Using methods discussed above, a relative importance was placed on each event with respect to other events in the analysis, allowing each report to rank events by their relative importance to safety.

The next step in the process was a comparison of important events from each study within each of the two categories of performance and safety. Events that repeated between studies or that showed a significant impact within a report were included on the composite important event list. Results of this selection process are included in the following sections.

After important safety related events were selected, they were used to identify vital components. Most of the industry studies indicate how components contribute to each event and significant components can be identified for the two categories. Important safety related events and their associated vital components are discussed in the following section.

2.2.2 Safety Related Components

Using the selection process discussed in the previous section, events with the greatest impact on safety (with respect to CDF) for the entire PWR power plant industry were determined. These results are presented in Table 2.2.2-1.

Table 2.2.2-1

Summary of Events with the Largest Safety Impact

1. Station black out (SBO)

2. Loss of coolant accident (LOCA) (Several Subcategories)

3. Steam generator tube rupture (SGTR)

4. Auxiliary feed water (AFW) (emergency feedwater) failure

5. Transient occurring without scram (also know as anticipated transient without scram (ATWS)

6. High pressure injection (HPI) failure

7. Low pressure injection (LPI) failure

8. Loss of main feedwater (MFW)

9. Loss of component cooling water (CCW)

10. Residual heat removal (RHR) system failure

11. Critical ventilation failure

12. Power operated relief valve (PORV) failure

13. Vital electrical supply bus failure

14. Steam generator power operated relief valve (SGPORV) failure

Events listed are not in any particular ranking order. Many events have general application to most plants. Others do not have uniform application, but warrant consideration due to their significant impact on safety. The following discussions summarize results of the survey of industry safety related studies. Each event summary lists documentation supporting the selection of the event and indicate some event effects.

A station black out (SBO) was selected since it was considered to have a large impact on increasing CDF by every industry study reviewed. One reason for its significance is that it has so many sequences that impact safety.

Loss of coolant accidents (LOCAs) were considered important by all of the industry studies. Similar to SBO, this event includes many scenarios which demonstrate the significance of LOCAs. More detailed discussions of LOCA and SBO scenarios are included at the end of this section when important components are designated.

Steam generator tube ruptures (SGTRs) are important in two Nureg 1150 evaluations, are a top ten ASP, mentioned in the survey of 21 PRA's and are

important in one specific plant PRA. SGTRs lead to core damage due to loss of primary inventory into the secondary system and the loss of decay heat removal due to a need to isolate the affected steam generator.

A loss of auxiliary feedwater (AFW) was important to one Nureg 1150 study, listed as a top ten ASP, ranked third for its frequency of occurring in ASP evaluations, ranked second in the 21 PRA summary report and was included in a specific plant PRA's. A loss of AFW can lead to a loss of decay heat removal thereby leading to core damage.

Anticipated transients without scram (ATWS) were important in all 3 PWR Nureg 1150 studies and mentioned in one specific plant PRA. This sequence is initiated by a transient that stops steam flow from the steam generators (a turbine trip, main steam isolation valve closure, etc) with no scram occurring. There is a potential for core damage to occur due to the fission process continuing in the reactor without sufficient heat being removed. In many cases, the reactor protection system is assumed to have failed. Normally quantitative analysis stops at the point of initiation of ATWS and the evaluations assume the sequence will continue to the point of core damage.

High pressure injection (HPI) system failure was among the top ten ASP, ranked fourth in frequency of occurring for ASP, ranked seventh in the PRA summary report and was mentioned in two specific plant PRA's. Failure of the HPI system could lead to uncovering of the core due to insufficient coolant make-up water during a wide variety of LOCA's.

Low pressure injection (LPI) system failure was ranked fourth in the PRA summary report, listed as an ASP, and mentioned frequently in one of the plant specific PRA's. A failure of the LPI system can lead to core damage in a fashion similar to the loss of HPI.

Loss of main feedwater (MFW) was ranked third in the top ten ASP, mentioned in the summary of PRA's report and mentioned several times in a plant specific PRA. A loss of MFW can lead to loss of decay heat removal means leading to core damage.

Loss of component cooling water (CCW) ranked tenth in the PRA summary report, was mentioned in the ASP report, and ranked first and tenth in two specific plant PRA's. Loss of CCW can lead to multiple component failures due to overheating or excessive thermal stress leading to core damage through a variety of sequences.

Failures of the residual heat removal (RHR) system was ranked in the top ten ASP and ranked fourth in the summary of PRA's report. During an accident which causes complete depressurization of the primary loops, the RHR systems removes residual decay heat from the core. Therefore, loss of the RHR system causes the core to heat up and increases potential for core damage.

Loss of critical ventilation was considered very significant by the PRA summary report and can lead to failure of a wide variety of electronic equipment, pumps, and motors that affect many core damage sequences.

A power operated relief valve (PORV) failure was ranked fifth by the summary of PRA's report and listed prominently in two specific plant PRA's. A PORV failure can result in core damage in a fashion similar to LOCA's.

Loss of a vital electric supply bus was listed in the ASP reports and considered significant in one plant specific PRA. This event could cause the loss of various components leading to failure of decay heat removal means.

A steam generator power operated relief valve (SGPORV) failure was listed in the ASP reports and ranked fourth by the PRA summary report. A SGPORV failure could lead to core damage through the loss of the decay heat removal capabilities of the affected steam generator.

All safety significant events are affected by system components. An example is one SBO sequence in which the event initiates with a reactor scram followed by a loss of offsite power, the failure of an emergency diesel, and battery depletion leading to loss of reactor coolant pump (RCP) seal which causes a LOCA and core damage. Each individual component in this sequence has an impact on the event's probability of increasing CDF.

Several components contribute to some important events while other events have only one major component contributing to the sequence. Safety impact events were analyzed using industry safety reports to determine critical components for each sequence. From this, a list of components with the largest safety impact are presented in Table 2.2.2-2. Associated important events from Table 2.2.2-1 are indicated in parenthesis.

TABLE 2.2.2-2

Components with the Largest Safety Impact

Note: The associated important event from Table 2.2.2-1 is listed in parenthesis

1. Diesel generator (SBO)

2. Offsite power buswork (SBO)

3. Steam generator tubes (SGTR)

4. AFW piping, pumps, controllers and valves (Loss of AFW and SBO)

5. HPI piping, pumps, controllers and valves (loss of HPI)

6. LPI piping, pumps, controllers and valves (loss of LPI)

7. MFW piping, pumps, controllers and valves (loss of MFW)

8. CCW piping, pumps, controllers and valves (loss of CCW)

9. RHR piping, pumps, controllers and valves (loss of RHR)

10. Ventilation system piping, pumps, controllers and valves (loss of ventilation)

11. PORV (PORV failure and LOCA)

12. SGPORV (SGPORV failure and SBO)

13. Electrical switchboards (loss of vital power and SBO)

14. Primary system piping and valves (LOCAs)

15. Emergency batteries (SBO)

16. Reactor control systems that send scram signals to reactivity control devices (ATWS)

17. Reactivity control systems control rods and drivers or borated water injection systems (ATWS)

18. RCP seals (SBO and LOCAs)

19. Main steam isolation valves (ATWS)

20. Reactor protection system (ATWS)

21. Turbine generator controls (ATWS)

2.3 Performance-Related Components

Selection of components with the greatest impact on power plant performance are discussed in this section. A brief background of studies used in the selection process is provided along with methods to merge inputs from various studies. An important performance-related events list is presented with vital component contributors to these events highlighted.

2.3.1 Performance-Related Component Selection Process

The selection process for important performance related components is similar to the process for safety related components. Several industry studies that evaluate component impact on power plant capacity loss were reviewed. Results from these studies were combined to determine components with the largest performance impact for the entire PWR community.

The studies reviewed were a series of reports by Stoller Power Division of RCG/Hager, Bailey, Inc for EPRI and a series of reports on Reliability Centered Maintenance (RCM) produced directly by EPRI. The Stoller reports, issued on a biannual basis since 1983, present and analyze operational data of nuclear power facilities. Data is primarily derived from monthly Operating Reports submitted to the NRC and supplemented by NRC "Gray Books", Licensee Event Report (LERs), operator experience and technical papers. These data sources provide the basis for setup of a plant operation analysis code that can evaluate performance sensitivity of a specific plant or the entire nuclear industry. A ranking of performance impacting events, based on capacity factor loss due to component failure or degradation, is provided by these reports (S-3,4,5,6). Rankings resulting from operational data collected from 1980 until 1988 were

used in this thesis. Changes in the effect of an event on performance were noted and used to predict future event impacts. Events predicted to have a major impact on future performance, or events which had a significant impact for greater than two report periods, were identified as important events fcr this thesis.

Along with data from the Nuclear Unit Operating reports, several of the most recent monthly status reports were reviewed. These reviews were used to supplement inputs from the Stoller reports and to obtain the latest indicators of capacity factor loss related components. Several Licensee Event Report (LER) summaries were reviewed to determine reasons behind the power plant's lost capacity highlighting potential important components (N-12,13,O-1,2).

EPRI RCM reports use a concept introduced by the aircraft industry in an effort to increase aircraft reliability and availability at an acceptable cost without reducing craft safety. EPRI has evaluated this concept for potential application to the nuclear power industry and several pilot programs indicated applications exist. Two projects representing a range of plant size and organization, as well as age and history of availability, were chosen to evaluate compatibilities and effectiveness of RCM with plant operation . These projects selected components to be evaluated for RCM based on detailed analysis of system relationships, current maintenance practices, (ensuring no safety impact), acceptable gain versus cost of revised maintenance action, and several other inputs. Through this process, components were prioritized based on the greatest impact on improved availability with no safety impact while reducing maintenance costs and focusing maintenance resources in the most effective

manner (E-2,3,4). One of the main objectives of the EPRI RCM project was to evaluate components with the largest impact on plant performance. Performance related events from the EPRI RCM studies were identified and used in this research.

Performance related events identified by the Stoller and RCM reports were evaluated. Events indicating commonalty between reports or significant performance impact were highlighted. These events were included in the final important performance related event list.

The Stoller and RCM reports indicate components affecting each event allowing the components with the greatest impact be identified. Vital performance-related components were then combined into a composite list.

2.3.2 The Selected Components

Final events selected for the largest impact on power plant performance are presented in Table 2.3.2-1. These events represent a merging of information from the nuclear unit operating data and the EPRI RCM projects. When determining input events from operating data, only events with a capacity factor loss of 0.2 per cent or greater were considered unless a significant trend was indicated.

Table 2.3.2-1

Events with the Largest Impacts on Capacity Factor

1. Steam generator tube rupture (SGTR)
2. Reduced thermal efficiency
3. Turbine blades and rotors failure or degradation
4. Reactor coolant pumps (RCP) and drives failure or degradation
5. Integrated leak rate tests
6. RCP seals failure or degradation
7. Uninterrupted power supply (UPS) failure
8. Main feedwater (MFW) piping leak or degradation
9. MFW pumps and drives failure
10. Turbine electrohydraulic control (EHC) and overspeed protection system failure
11. Reactor vessel internals, flanges and seals failure or degradation

12. MFW chemistry problems

13. Condenser tubes leaks or fouling

14. Diesel generators failures

15. Control rod drives failures or degradations

The order in which these events are listed does not represent a ranking. Some events show a consistently high impact on plant performance (capacity factor). Other events were included due to an increasing trend in impact. In all cases, events were selected because there is an indication that the event should be evaluated for improvement.

Similar to the safety selection process, the performance selection process uses the important performance event list to determine components with the greatest impact on performance. Nuclear operating performance and RCM reports were used to identify components that affect each event. Table 2.3.2-2 lists components that have the largest impact on nuclear power plant performance with the associated important event from Table 2.3.2-1 listed in parenthesis.

Table 2.3.2-2

Components with Largest Impact on Capacity Factors

Notes: (1) Associated important events from Table 2.3.2-1 are in parenthesis

(2) (same)* indicates the associated event from Table 2.3.2-1 is the same as the component.

1. Steam generator tube rupture (same)*
2. Steam leaks through valves, flanges, etc (thermal efficiency)
3. Inefficiently operating auxiliary steam loads (thermal efficiency)
4. Leaking feedwater heater tubes (thermal efficiency)
5. Inefficient moisture separator (thermal efficiency)
6. Thermal shields (reactor vessel internals)
7. Core barrel flow channels (reactor vessel internals)
8. RCP seals (same)*

9. Turbine blades and rotors (same)*

10. Reactor coolant pumps and drives (same)*

11. Uninterrupted power supply (same)*

12. MFW piping (same)*

13. MFW pumps and drives (same)*

14. Leaking main condenser tubes (same)*

15. Control rod drives (same)*

16. Turbine EHC or overspeed (same)*

17. MFW chemistry (same)*

18. Circulating water system fouling (condenser tubes)

19. Fuel oil piping leaks (diesel generator)

20. Overspeed governors (diesel generator)

21. Various adverse conditions leading to excessive crankcase pressure (diesel

generator)

22. Equipment associated with the integrated leakrate tests (same)*

2.4 Chapter Summary

Selection processes used to determine components with the largest impact on power plant safety and performance are discussed in this chapter. These components can be further studied to determine how they fail or degrade thereby identifying vital monitoring needs. Technology can then be surveyed for the best applications to improve these important components.

It should be noted that all studies used to determine important safety or performance related components contain a degree of uncertainty. Since several studies were used to determine the final important components, the effect of these uncertainties have been reduced; however, the component selection process may not be exact.

Power plants continue to modify systems, change component relations and alter operating procedures which can effect the selection of important components. For example, as cross-ties between co-located power stations are installed the significance of some components may be reduced. Therefore, important components selected in this thesis may be affected by industry-wide plant modifications or changes in operating procedures.

Another analysis may select slightly different important components. This thesis represents an attempt to determine the most likely important components using available information and hopefully, will not only serve as a focus for future improvement efforts, but also to motivate a critical analysis of future important component selection.

Components identified in this chapter are used to determine monitoring needs of the nuclear power industry. These needs are discussed in the following Chapter.

Chapter Three

Monitoring Needs

3.1 Introduction

The previous chapter discusses how industry studies identify important safety and performance related events and determine associated components having the largest impact. Failure or degradation modes of these components may be placed into common groups allowing monitoring needs to be identified. This process is discussed and summaries of possible important monitoring requirements are presented.

3.2 Identifying the Monitoring Needs

Several reports were used to identify common problems with important components determined in Chapter Two. Failure or degradation modes were found and categorized based upon the mechanisms involved. For example, those failure or degradation modes involving electrical faults were placed in one category, while modes involving through-wall or component leaks were put into another group. These mode categories were used to determine the most important monitoring needs summarized in Table 3.2-1. Table 3.2-2 illustrates how the needs were identified. The left column indicates monitoring needs and the right column shows some of the failure or degradation modes for important components, identified in Chapter Two, that lead to the need selection.

Table 3.2-1

Summary of Monitoring Needs

1. Oil analysis
2. Pump condition monitoring
3. Piping, tube and vessel material internal monitoring
4. System overall health monitoring
5. Diesel air start and governor monitoring
6. Electrical fault identification
7. System operability verification
8. Battery condition monitoring
9. Steam generator internal monitoring
10. Reactor internal monitoring
11. Valve condition monitoring
12. Turbine condition monitoring
13. Integrated leak rate testing
14. Reactor coolant pump seal system monitoring
15. Condensate and feed chemistry monitoring

Table 3.2-2

Need Identification Process

Needs	Some Failure or Degradation Categories
1. Oil Analysis	Excessive component wear
	Diesel lube oil fuel dilution
	Pump or turbine oil component needs
	Excessive corrosion or contamination
	Oil additive breakdown
	Control oil modes
2. Pump condition monitoring	Impeller erosion, cracking, etc.
	Bearing, shaft etc. seizing
	Casing leaks or rupture
	Excessive vibration
	Valve failure or operation affects
	Fail to start (mechanical reasons)
	Shaft cracking or severing
3. Pipe, tube and vessel material internal monitoring	Diesel engine fluid system leaks or ruptures
	Fatigue or brittle failures
	Turbine blade cracks or breaks
	Wall thinning due to corrosion, erosion, etc
	Intergranular deterioration
	Steam generator or condenser tube leaks

4. System overall health monitoring	Thermal losses Layered maintenance approach (discussed in Section 4.2.15) Several failure modes Electrical faults
5. Diesel air start and governor monitoring	System failures or degradations
6. Electrical fault identification	Component fails to start (electrical reasons) Electrical bus inconsistency Electrical overheating or fires Setpoint drifting MOV failure or degradation Transformer, ABT, circuit breaker or other power supply fault
7. System operability verification	Diesel fails to start PORV operates improper or fails Reactor control verifications
8. Battery monitoring	Thermal induced grid and connector oxidation Plate and grid swelling Container and cover deterioration

9. Steam generator internal monitoring	Foreign material exclusion Tube thinning, denting, fretting, etc. Internal structure degradations
10. Reactor vessel internal monitoring	Thermal shield support cracking Water jet impingement effects Fuel rod swelling Core basket inlet fouling
11. Valve monitoring	Checkvalve faults MOV, SOV, etc faults Mechanical valve leaking, binding, etc Disk stem severing
12. Turbine condition monitoring	EHC faults Cracked disks Water impingement effects Broken blade damage
13. Integrated leak rate testing	Test not conducted at operating pressure, or temperature Test impact on operations
14. RCP seal system monitoring	Seal water contaminations Loss of seal flow Fouling of seal system

15. Condensate and feed chemistry monitoring	Startup chemistry transients Accelerated corrosion Foreign material effects SCC effects

Monitoring needs are not listed in a ranking order. Some of the needs apply to many important components while others apply to only one or few, but are significant due to their substantial effect. The following discussions indicate reasons for selecting each need along with a description of the need.

Oil system analysis is used to predict failure of several important components. In addition, oil analysis can detect lubricant breakdown, component part wear and foreign material introduction, predicting the overall condition of a component. Many systems allow oil samples to be taken via samples lines while the components continue to operate offering little impact on system operation.

Pump condition monitoring, affects a large number of important components and includes the determination of a pumps overall capacity and conditions of pump elements, such as bearings and impellers. Excessive vibrations can indicate pump imbalance or internal part failures, while faulty associated equipment can cause a healthy pump to operate improperly.

Piping, tube and vessel material condition have a major effect on many important components due to fatigue, embrittlement, erosion, corrosion etc.

phenomena that must be closely monitored. In addition, several joining processes require internal inspections to ensure proper system integrity. Due to these problems, there is a need to determine the internal conditions of these structures (N-9).

Evaluating overall health of a component and its associated system can identify problems for most safety or performance related important equipment. Health monitoring can improve safety by identifying precursors to component failure or degradation that have safety impacts. Overall system performance may be improved by monitoring the thermodynamic, mechanical or electrical condition of a component and comparing results from each process.

An important safety-related component is the emergency diesel. Diesel failure and degradation modes indicate problems with the air start and governor systems which identifies some monitoring needs (N-13). Several other diesel monitoring requirements were grouped into other similar categories.

Identification of electrical faults is a monitoring need for several components. These component needs range from system instrument and control to major switchboards faults. Monitoring needs include short or ground detection, continuity checks, and electrical system operability checks to ensure the system functions as designed (N-9, S-4,5).

Several important components remain idle until needed for a safety or performance related reason. These components identify a monitoring need to determine if standby components will function as designed upon demand. An example of this need is the emergency diesel. A monitoring system could

monitor diesel air start, lube oil, fuel oil, cylinder, and other associated system conditions to determine if the diesel is ready for start up. Power operated relief valves and the AFW system are other key examples of this monitoring need.

The battery was selected as an important safety related component since several adverse battery conditions can reduce its capacity and limit the effectiveness of this vital equipment. Some of these conditions are thermal swelling, grid dislocations, connector oxidation, container/cover cracking, and separation deterioration (N-9).

Steam generator tubes were selected as safety and performance related components. Monitoring the material condition of tubes was discussed earlier. However, other tube problems can be identified by an internal inspection of the steam generator. Some examples of these tube problems are: the rubbing of tubes against tube supports, tube denting caused by corrosion, sludge piles that lead to stress corrosion cracking (SCC), high velocity water jet vibration/fretting wear, general surface pitting and foreign materials that may cause tube damage (G-3,S-5).

Several reactor vessel internal structures were listed as important performance related components. Some of the problems that may be identified by an internal inspection of the reactor vessel are as follows: inlet/outlet nozzle thermal and mechanical fatigue and embrittlement, fuel channel inlet flow grid deterioration/channel misalignment, degradation of the thermal shield supports, and instrument/control rod drive mechanism (CRDM) housing fatigue (S-4,5).

A major impact on power plant safety and performance is the condition of valves in the facility. Valve categories include: motor operated valves (MOV), solenoid operator valves (SOV), manual valves, and check valves. Each of these categories have monitoring needs similar to the other types which allows the use of common equipment. Conversely, some needs are unique to one valve type, requiring the development of specialized equipment. (N-9, S-4,5).

Turbine generators and associated systems were selected as performance related important components identifying a need to monitor turbine conditions. Some of the turbine problems that require monitoring are: the turbine electrohydraulic control (EHC) system, overspeed protection system, cracked blade buckets/pins and cracked or water eroded/cut rotors and disks (S-5).

Integrated leak rate test equipment was identified as an important performance related issue. Current test methods require complicated procedures and have a major impact on plant maintenance periods signifying the need for improved testing methods (S-3,4,5,6).

RCP seals were selected as performance and safety related important components. Some of the monitoring needs of these components are: seal water purity and chemical levels, seal flow passage condition, system lineup status and seal integrity or positioning due to mechanical or thermal shock (N-2,3).

Plant performance is impacted by condensate and feed water chemistry problems. Since system chemistry has an influence on MFW and AFW systems integrity, system chemistry probably affects plant safety as well. Monitoring

needs include: determining fluid pH, conductivity, and oxygen content; identifying foreign materials; and determining system corrosion rate by measuring corrosion product content of the system fluid (S-4,5).

3.3 Chapter Summary

This chapter discusses various monitoring needs required to improve power plant safety and performance. Failure and degradation categories were developed using historical data for the important components identified in the previous chapter. These categories were used to highlight the most significant monitoring needs. The extent to which these needs are met can determine the degree of improvements made on important components. Effectiveness of monitoring methods will depend on the accuracy with which improved technics monitor component conditions.

Impacts on plant operations by monitoring methods should be considered. Using methods that function under normal operating condition may provide more useful information about component conditions. For example, testing a valve at full system pressure gives a better indication of the true condition of the valve than testing with the system depressurized. Plant safety and performance is improved since test accuracy increases. In addition, on-line monitoring has less affect on plant operations resulting in lower capacity factor losses.

The following chapter uses monitoring methods identified in this chapter to focus a survey of industry personnel, research institutions and the literature for technology that may offer improvements.

Chapter Four

Survey of Technology

4.1 Introduction

This chapter summarizes the findings of a survey of technology for improved component monitoring methods. Monitoring needs identified in the previous chapter were used to focus the survey allowing concentration on technological applications and research in areas that have the greatest influence on power plant safety and performance.

4.2. Technology Categories

Several technologies which have some application to needs of the nuclear power industry have been identified. Each of the following subsections summarize some of the theory, describe principles, and discuss potential future developments of these methods. Application examples are given when it benefits the technological description and, in some cases, improvements over current monitoring methods are presented.

4.2.1 Lubricant Analysis

Lubrication analysis methods determine the condition of the lubricant and can indicate component wear or foreign material entry. Lubricant condition monitoring is important to ensure the lubricant functions as designed. Component wear analysis is important in determining when component part replacement may be required. Foreign material exclusion is important to ensure lubricant channels remain clear and to prevent foreign material damage to

lubricated surfaces.

Several tests are used to indicate lubricant condition. One of these tests checks for solids or moisture in the oil and can indicate component wear or damage. Moisture can lead to reduced lubricant effectiveness or corrosion of component internals.

Some tests check for milky or darkened appearance of lube oil. Milky appearance indicates water emulsion or excessive particulates. Darkened appearance indicates oil deterioration through oxidation.

Infrared spectrography tests check for organic contaminants and oil oxidation. In diesel engines, this test can indicate fuel dilution, fuel soot or nitrate contamination. This test can indicate reduced lubricant effectiveness, increased wear, the presence of corrosion products, and reduced lubricant oxidation inhibitor.

Particulate counting tests can indicate the concentration of solids in the oil indicting system cleanliness. For systems with close tolerances that are subject to fouling, this test is important. System malfunction in control systems or component overheating in reciprocating or rotating equipment may result from this type of contamination.

Oil acidity or pH can be an indication of new oil quality. Abnormal readings can indicate reduced oil film protection or decreased ability to neutralize acid contaminants.

Oil viscosity is a measure of the oils resistance to flow. Abnormally low viscosity can indicate a reduction in the oil films ability to limit unwanted metal contact. Reduced viscosity can be caused by the introduction of oil impurities like water, fuel oil and solvents.

Concentrations of metal wear products, additives and contaminants can be measured by spectrographic analysis. Data can be easily plotted allowing trend analysis to track the development of problems. Component wear product concentration trends may show excessive wear patterns or indicate that part replacement is warranted. Spectrography is limited to detecting up to 12 microns maximum particle size. Trend analysis may also indicate oil replacement is required due to abnormally high ferrous materials.

Microscopic analysis of wear particles may help determine the source of the particles. Wear particle categories have been established based on particle appearance. Comparing sample appearance to pictures of these established categories can identify possible particle sources. Scanning electron microscopes may further enhance particle identification and matching. Increased magnification of the electron microscope makes it easier to determine trends for additives or contaminants.

Ferrography can detect wear particles up to 250 microns in size allowing detection of larger wear particles and solid contaminants than spectrography. Research has indicated the presence of larger particles may be an early indication of wear; as a result, ferrography may be a useful component wear monitor. Similar to spectrography, trending methods may assist the analysis of

particle categories.

All of the lubricant analysis methods monitor chemical and physical properties of the lubricant. These results indicate the ability of the oil to reduce friction between metal surfaces and limit heat generated in the equipment. Excess friction or abnormal heating can cause reduced component lifetime (N-12).

Analysis methods that detect wear products can be very helpful in predicting when component replacement is required. By measuring the nature and concentration of wear particles in the lubricant, the condition of equipment component parts can be determined.

Recent developments in advanced filtration systems have enhanced evaluations of lube oil particulate. Some systems place a sensing coil between two poles of an electromagnet and measure the rate of buildup of ferromagnetic material. This method indicates concentrations of ferromagnetic particulate in the oil (C-2). Other improved systems use high efficiency small hole filters and dryer systems. These devices can measure particulate without significantly affecting system flow (N-12).

4.2.2 Eddy Current Testing

Eddy current inspection methods are based on an electromagnetic induction phenomenon. A magnetic field is generated when an alternating current is placed through a conducting coil. The magnetic field encircles the coil and when this region contacts another conductive material, free electrons in the second conductor move in a direction perpendicular to the magnetic field. These induced currents are called eddy currents.

These eddy currents produce a secondary magnetic field that interacts with the coil by affecting coil impedance. The induced current and secondary magnetic field remain under the coil as it moves over the surface of the material. Defects and variations in material properties affect the flow of electrons and are indicated by changes in coil impedance (M-3).

Electrical properties of the material and flaw characteristics must be considered for eddy current non-destructive evaluation (NDE) to be effective. This leads to the need for the proper selection of test frequency, transducer size/configuration and inspection technique (E-7). Recent experience with service water heat exchangers shows that improper assumptions about material properties lead to large errors in flaw location predictions. (B-3).

Eddy current instrumentation consists of multifrequency and parameter mixing equipment. Frequency equipment can generate applied voltages with distinct frequencies, adjustable signal gain and variable phase angles. Mixing modules combine frequencies to filter unwanted interfering signals.

Data may be analyzed by a multifrequency or a multiparameter method. In the multifrequency method, data from each frequency is treated separately allowing an analysis of eddy current response as a function of frequency (E-7). Optimum test frequencies are determined by using a calibration standard, which in many cases, is based on ASME inspection codes and laboratory predictions (B-3).

Multiparameter methods combine data from individual frequencies by vector addition. This process can eliminate signals that do not directly relate to the desired test data.

Transducer selection is dependent on component characteristics and the nature of the material flaws. For example, very small defects need to use a small, shielded, ferrite core probe that can operate at high frequencies. Component arrangements may further restrict the probe geometry.

Variations in component exteriors cause the in-plane position of the probe to vary as it moves across the inspection surface. This unwanted probe movement can affect test results and reduce depth of penetration. Therefore, the probe must be maintained in direct contact with the test surface.

Automated test equipment has been shown to reduce effects of losing probe and test surface contact. In addition, automation reduces intensive labor requirements of hand scanning. By using automatic eddy current systems, large surfaces may be inspected with an improved accuracy over hand scanning equipment and in much less time (B-3).

4.2.3 Ultrasonic Imaging

Ultrasonic imaging methods use sound transmitting and receiving devices to determine the thickness and interior condition of materials. These devices measure the time for a sound signal to be transmitted and reflected back to a source. This time will depend on the amount and type of material the sound travels in. Presence of flaws, wastage and other material degradations will affect the sound transmission. Corrections must be made for pipe or component interfering structures, like elbows, sleeves or unions.

Thickness measurements by ultrasonic imaging can be very accurate and efficient. Most other thickness measurement devices measure only one depth at a time. Ultrasonic equipment can make thousands of measurements in a region instantaneously.

Ultrasonic equipment can produce three-dimensional images which allow the analyst a clear picture of flaw orientation. The equipment can make accurate measurements of flaw dimensions allowing interpretations of the magnitude and effect of flaw conditions on material integrity.

For ultrasonic imaging to be effective, sound must be capable of penetrating the maximum depth of components. Some presentations of results appear like a topographic map with depths of voids and flaws indicated by colors. A cursor may be used to obtain thickness and other information from points of interest directly from the presentation screen.

Ultrasonic equipment normally consists of a scanner (transmitter/receiver), thickness/image analyzers, display equipment and a data storage unit. The

scanner consists of a transducer mounted on a positioning system. Exact locations of the transducer are measured from a known starting point. This point may be used for each subsequent inspection to allow correlation between tests. Position information is matched with measured data by a data storage device creating a direct correlation between collected data and component locations. Scanners normally strap onto the component to be inspected with a solid sound path provided by an acoustic enhancing oil or grease. Accuracy of these systems can be up to 0.001 inches under ideal conditions (N-12).

Several recent developments have improved ultrasonic imaging. Some of these improvements are digital image enhancement, imaging in cast stainless steel and surface beam distortions correlations.

Ultrasonic methods can be improved by digital processing of images. Previously, imaging has been very dependent on operator interpretation. Since each analyst may evaluate images differently, the exact location and characteristics of the same flaw is subject to operator experience and technique. Trending of ultrasonic results is very difficult due to the wide range of results (N-12).

Digital processing of ultrasonic images may improve some problems associated with signal interpretation. NES Dynocon, INC. has developed an ultrasonic data recording and processing system (UDRPS). The EPRI NDE Center evaluated UDRPS and determined enhanced detection and sizing of near surface and embedded flaws in nuclear pressure vessels is possible. The system

is compatible with automatic scanning systems and most other ultrasonic equipment. UDRPS was also found suitable for older pressure vessels with high background noise which normally are difficult to inspect (E-7).

Digital processing of ultrasonic images can reduce the affects of interfering electrical signals (noise). The equipment scans components obtaining hundreds of readings per square inch. Images are compared and, through the use of computer programs, the best data is obtained (M-2).

Digital processing of images allows trending of ultrasonic data. Operators can call up previously recorded images for comparison with current pictures. Trends can be detected in crack length, width and depth data (N-12). Inconsistent results, due to varying interpretations from different operators, is eliminated since one operator can analyze a series of collected data. Analysis results reflect actual conditions more accurately. It is easier to see defect conditions by comparing a series of images taken under identical computer controlled conditions. Previous methods compare images taken by different operators reflecting operator biases.

Ultrasonic examination of cast stainless steel components experience excessive noise interference, insufficient penetration and false indications of flaws. A major factor contributing to these problems is the anisotrophy of the material. Cast austenitic structures have a tendency to crystalize along a single axis causing beam skewing and excess beam divergence. Researchers at the Ames Laboratory at Iowa State University are investigating improvements by

comparing experimental beam profiles with beam propagation theory. A better understanding of wave behavior in stainless steel components may result from this work (T-1).

Ultrasonic inspections are greatly affected by the conditions of the surface through which sound must be transmitted. Many factors can give a surface an uneven finish that will interfere with the transmission beam from ultrasound equipment. These rough surface effects can cause unclear images or mislocation of flaws.

Researchers at the Center for NDE at Iowa State University are developing models to predict the influence of uneven surfaces on ultrasonic inspection of nuclear power plant components. These models may provide a baseline for establishing surface finishing requirements. Battelle Pacific Northwest Laboratories, through support of the NRC, is providing data to help develop and validate the models (T-2).

4.2.4 Radiography

Radiography uses X rays to detect flaws in the internals of component walls, casings or structures. In addition, the analyst may look through system pressure boundaries to identify foreign material, loose parts or other component internal problems. Recent research has developed real time radiography, allowing inspection results to be viewed during the analysis process rather that waiting for film processing.

Current X ray applications, using radioisotopes, are limited to steel sections of less than six inches. Thicker sections require much longer exposure time and

since these applications emit stray radiation, much of the inspection area must be maintained off limits to personnel. Therefore, impact of the current systems on plant operations can be substantial and images produced can be of poor quality (N-12).

Real-time equipment uses a linear accelerator to achieve high energy outputs on a small focused area. This results in a much higher penetrating power than radioisotopes. The size of the linear accelerator is inversely proportional to the frequency of the RF carrier. Therefore, through energy optimization, and use of accelerators of very high frequency, the size of the X ray head can be made small enough to fit into most inspection areas (L-1).

An associated filmless imaging system has been developed allowing real-time analysis. Placed opposite the accelerator, the filmless unit is a composite fluroscreen and detector array. Accelerator and detector arrays may be rotated around the component giving a three-dimensional effect providing an aspect feature to the images that may greatly enhance inspection capabilities (N-12, L-1).

By traversing the unit along a pipe or wall structure, internal inspection of an entire section is rapidly completed. Inspections of this type by previous methods would require much more time and have a greater impact on plant operations.

Imaging of moving parts is feasible by using high-speed processing allowing the previously unavailable evaluation of the dynamic behavior of component parts. This is particularly helpful for problems that can not be identified unless the system is in operation.

Since the units use an electronic X ray source, proper radiation protection measures must be taken. However, using a video camera reduces the exposure to personnel since specimen viewing may be conducted at a remote location. Control of the radiation source is much safer due to radiation not being emitted until the accelerator is energized. Electrical cutout switches that allow strict control of emissions are easy to install.

Filmless imaging can be easily recorded for later analysis or comparison to future inspections of the same component. This storage system makes trending of inspection data easier. In addition, filmless units can use digital image processing for image enhancement, increasing the improved sensitivity of real-time radiography over radioisotope methods.

Further radiation head modifications may improve unit access to compact piping configurations. The accelerator and remaining head components can be separated and joined by a flexible waveguide. In this improved application, energy output can be increased to improve image quality and increase penetration lengths (S-7).

4.2.5 Visual Systems

Many visual systems are available that can detect problems existing inside components. These systems can enter limited access areas and some do not require the system to be completely opened. Remote sensing devices can allow inspection of areas with excessively high radiation. Some of the systems available are borescopes, flexible fiber optics, telescopes/binoculars, periscopes, cameras and the unaided eye. Some of these systems can be repositioned by robots.

Borescopes include an optical lens or glass optics. Normally shorter than three feet and thin, mirrors or glass are used to reflect or magnify the images.

Fiber optic devices can be made more flexible and longer than borescopes, facilitating easy bending, which allows extension to remote locations around turns and redirections. Some devices have several channels for image transmission, light enhancement or special features including inspection aids (i.e. forceps, etc) or retrieval devices.

There is a wide variety of camera devices of varying character for different applications. Some models are very small, less than an inch in diameter, while others contain many accessories, such as lighting, retrieval, measuring, and other inspection aids (N-12).

Camera systems can be repositioned by remotely operated robots. The electronically transmitted signal produced by the camera may be computer enhanced for greater clarity and detail.

An example of this type of system was developed by R. Brooks, Associates, Inc. This system is a miniature camera and retrieval system that can enter access ports as small as 2 inches. Uprighting itself after entry, the device can extend up to 10 feet from the access point for remote inspections. The device can operate with a 360 degree panoramic and 270 degree tilt camera which has remote focus and camera lighting, and provides excellent visual results (G-4, B-4).

Several other companies have similar systems. Many of these companies can design a remote camera system to meet specific inspection needs.

Camera systems can easily record image data making the process of trending component degradation and comparison to previous data easier. In addition, one analyst can evaluate a series of recorded data removing some of the subjectiveness of previous systems (N-12).

4.2.6 Acoustic Monitoring

Noise monitoring devices detect sound generated by operating equipment. By detecting variations from the normal noise patterns, component problems may be detected. Leaking valves or tubes are identified by detecting flow noises of fluids or gases through small cracks or orifices. This flow generates sound in the form of turbulence, cavitation, flashing of water into steam, and mechanical vibrations due to pressure fluctuations. Component mechanical problems are detected by identifying noise patterns that deviate from normal due to vibrations, system misalignment or reduced component capacity. Electrical problems may be identified by buzzing, popping or frying sounds (N-12, B-2).

Ultrasonic monitors detect sound at frequencies above the highest level detectable by the human ear (20 kHz). Their frequency range is usually limited to 20 to 100 kHz which helps screen out the majority of interfering background noise and is the optimum range for most diagnostic needs.

Due to their relative high frequency, ultrasonic sound waves are very short and travel in straight lines. These waves can not penetrate solids but do filter through very small openings. Conversely, audible waves are long and penetrate walls and machinery. By using ultrasonic monitors, the large amount of audible machinery noise is automatically filtered out making component wear or fault noise generated at ultrasonic frequencies easier to detect (F-1). In addition, the straight line radiation of ultrasound make its source easier to locate than audible noise (B-2).

Many component initial failure phases originate above human ear detection ranges. Since ultrasonic devices can detect these problems before the human ear, they make excellent early warning equipment.

Ultrasonic probes measure sound amplitude, intensity and frequency. Electronic circuitry converts the ultrasonic-received signal into the audible range to allow the operator to conduct qualitative analysis. Most instruments use a battery to allow the unit to be portable giving greater flexibility. Intensity strengths can be displayed on an analog meter. Some models use filters to remove interfering signals and use meter response controls for real time averaging. Volume control and sensitivity selections can be used to detect and

enhance weaker signals (B-2). As with any data that is received electronically, ultrasound signals may be digitized for computer enhancement, storage or trending.

Ultrasonic detectors have two modes of operation, scanner or contact mode. In scanner mode, the instrument simply monitors the airborne noise levels in the vicinity of the component. In the contact mode, a metal rod acts as a waveguide between the component and the detector. The waveguide is stimulated by ultrasound occurring on the other side of the component boundary.

Ultrasonic monitoring systems may use a tone generator as an ultrasonic source when a system can not be pressurized to allow testing. Placing the transmitter inside the component, allows the scanner on the outside to check for sonic penetration. This process can be used to detect leaks prior to placing a system into operation (B-2).

Directivity of an ultrasonic probe may be enhanced by a slip-on rubber focusing sleeve. Since ultrasonic waves can not penetrate rubber, signals from competing sources are eliminated effectively amplifying the signal from the desired source (B-2).

4.2.7 Vibration Analysis

Abnormal shocks or vibrations from rotating or oscillating equipment can be used to predict component failure or detect degrades. Analysis methods must distinguish between normal and abnormal vibrations.

The frequency of various vibrations detected from a component directly relate to the geometry and mode of operation of the machine. Using data collected from previous component failures, frequency and defect-type relationships may be established. Comparison of test data to normal condition data can identify problems (B-1, N-12). It is important to establish a large data base to insure all normal system characteristics are accounted for.

Identification of specific component problems can be complicated by random system background noise and multipath reverberations in structures. A number of techniques have been developed to resolve these issues. Some of these methods are rather sophisticated and involve time averaging and noise cancelling through mathematical computations (W-1).

Three important characteristics of vibration analysis are displacement, velocity and acceleration. Displacement monitoring methods use the amount of movement of component surfaces supplemented by frequency values. Velocity is the speed of displacement of the monitored surface. Most methods use the root mean square of velocity to compare data. Acceleration is the rate of change of the velocity of the vibrating surface. Using Newton's first law, acceleration gives an indication of the forces generated by the vibration.

None of the three characteristics yield a distinct advantage over the other two. Displacement or proximity probes are not affected by interfering debris; they are easy to use and are not greatly affected by temperature change. However, they have a limited fault detection frequency range, require large support equipment and are sensitive to change in nearby materials and

magnetic fields.

Velocity transducers are easy to use, have a wide fault detection frequency range and measure absolute motion that is less susceptible to interference from background noise. Disadvantages of velocity measurement methods are that the equipment is expensive, difficult to maintain and hard to calibrate.

Accelerometers are small, rugged and the cheapest of the three mechanisms. These devices have the largest fault-detection frequency range and high-temperature resistive units are available. However, they are hard to calibrate, are sensitive to electrical and background noise, and have reduced accuracy under low-frequency varying temperature conditions.

There is a wide variety of vibration analysis support equipment available. Many of the devices are portable and include microprocessors that provide several real-time features. Sensors collect signals from mounts on the surface of the machine. Some devices are permanently installed and collect data in a continuous or periodic fashion depending on the mode of the machine and type of monitoring required.

Microprocessor devices have become rather sophisticated. Some of their functions convert collected signals into easy manipulated digital values, present data for real-time analysis, record messages at the time of data collection, and present a means to efficiently transport data to collection centers. A microprocessor can compare current test reports to normal baseline information stored in the processor and determine if a problem exists immediately following data collection.

Information received by the microprocessor can be transferred to a computer. Most systems have developed specialized software to aid the analysis process. Computers can conduct a more detailed analysis than portable microprocessors including comparison of current data to enhanced data bases. Each measurement is added to the data base for use in future analysis. Automatic report and scheduling functions can be provided by the computer (N-12).

4.2.8 Computerized Data Processing

Computers and microprocessors can improve data evaluation and reduce human errors. Computers can collect, store and correlate data received and enhance information from many monitoring methods.

By reducing the amount of data manually recorded or processed by humans, computers greatly decrease the probability for errors and improve accuracy of analysis results. Computers allow the operator to electronically transfer data between processing points, reducing the likelihood of error due to improper manual movement of information. In addition, computers can plan collection schemes, indicate reading tolerances, digitally collect different types of signals and automatically assemble supplemental information when alerted to potential problems (N-14).

Computers can enhance data collected through the use of various data processing programs. As discussed in previous sections, computers can enhance raw data collected from most monitoring devices. Improved images in radiographic or ultrasonic systems and enhancement of vibration measurements

are examples.

Computer processors can predict equipment age through assessment of plant stresses. Monitoring systems use installed instruments to record plant operating conditions and computer programs perform calculations to predict structural stresses that have been experienced. From a stress history, the computer system can predict fatigue damage, estimate crack propagation and assess crack stability. These results can be used when making decisions concerning plant operation, inspections, maintenance and repairs (H-2).

Computers can greatly improve the online monitoring process. Since the amount of data the computer can collect and analyze is very large, many aspects of system operation can be analyzed simultaneously. Thermodynamic, mechanical and electrical characteristics can be combined to get an indication of a system's conditions. Since each combination of these characteristics corresponds to a unique component condition, more accurate and faster fault locating can be made (S-8).

Recently several organizations have used computer processors to develop systems with artificial intelligence. This process uses information provided by human experts to train neural networks. In some cases, these systems have shown 100 per cent agreement with human classification (W-1). The use of automatic neural networks can analyze component conditions much more frequently and consistently than human analyzers. In addition, the knowledge of the most experienced operators can be more effectively used.

4.2.9 Non Intrusive Flow Measuring

Doppler flow monitors, time difference devices, and tracer sensors are some common non-intrusive flow measuring devices. Doppler monitors reflect sound or light off particles suspended in the flow stream. As the particles move away from the source, successive waves strike the particles farther downstream creating a doppler frequency shift in the reflected signal. The amount of frequency shift is directly related to the speed the particles are moving and indicate the fluid flowrate.

Time difference transducers use two transducers separated by a precise axial difference along a flowstream. One transducer transmits downstream and the other one transmits upstream. Downstream transmissions will reach the other transducer in less time than the upstream transmissions due to the flow of the fluid. Time differences are related to the stream flowrate. Impurities in the flowstream, improper placement of the transducers and incorrect time measurement can introduce inaccuracies in this method.

Tracer sensors use the change in trace element concentration with time to estimate flowrate. Trace elements are introduced upstream and their concentration monitored downstream. The time of the trace element introduction must be carefully correlated to downstream concentration measurements. Analysts must ensure that downstream samples accurately represent the main flowstream tracer concentration.

Stream flow profile can affect all of the flow sensors. If the flow swirls or fluctuates, sensor accuracies may be affected. This can be important when smooth laminar flow shifts to rough turbulent flow or when flow travels around a bend or obstruction (N-12).

The non-intrusive flow measuring devices offer an improvement over previous sensors. Most of the old flow indicators use pressure changes in a venturi restrictor to indicate flow. These systems are subject to pressure fluctuations, clogged sensing lines and other inaccuracies. By measuring flow by direct non-intrusive methods, these inaccuracies are avoided.

4.2.10 Stress, Strain and Torque Measurement

Most stress, strain and torque measuring equipments use electronic sensing devices called strain gages. These sensors use the property of conductors to change resistance when stretched or compressed . Strain gages are attached to the surface of sample material and electrical measurements indicate the material strain. By using Young's modulus and other mechanical relations the stress or torque may be calculated from the strain values.

Strain gages measure strain in perpendicular directions. Measurements for other directions are calculated using Mohr's relationships (C-3). These gages are calibrated for a set baseline condition and indicate stress, strain and torque changes from that condition.

Electrical signals produced by strain gages may be fed to a computer for enhanced analysis, improved presentation, or long term data storage. Output may also go to a plotter or other data analysis device. Evaluation of the strain (stress or torque) history can predict the amount of mechanical damage the test component accumulates over a period of time.

Since conductor resistance changes with temperature, strain gages must be temperature corrected. They also suffer fatigue damage with time and some gage instrumentations suffer from circuit nonlinearity. When used near electric or magnetic fields, the strain gage circuitry may be affected. All of these effects may be compensated for by the analyst. However, compensating techniques require operator skill and may result in inaccurate results (N-12).

4.2.11 Temperature Sensing

Sensing devices determine the heat transmitted by a component by measuring its temperature. These measurements can be compared to the temperature of the surroundings to indicate the amount of heat energy associated with a component and used to indicate equipment conditions.

Two categories of temperature sensors are non-contact and contact detectors. Non-contact devices analyze the electromagnetic energy emitted from all objects above -273 degrees C. Molecules of a material vibrate depending on material temperature and molecular structure. Since these molecules carry an electrical charge based on their atomic structure, molecular movements cause electromagnetic energy to be emitted (B-5). The rate at which the atomic particles move determines the wavelength of the emitted energy. Since the material's temperature relates directly to its atomic movement, there is a relationship between radiated wavelength and temperature.

Sufficiently hot objects can emit visible radiation by a phenomenon called incandescence. The color and intensity of this light can be an indication of an object's temperature. This fact is used extensively in the steel industry where visible temperature properties are used in the production process (M-4, R-12).

There is a large amount of energy emitted outside of the visible wavelength range. Much of the visible radiance intensity below 1000 degrees F is so low it can not be seen (I-1). This makes the measurement of radiated wavelengths above the visible range (about 0.4 to 0.7 micrometers of wavelength) necessary. Most infrared equipment is most effective from 3 to 5 or 8 to 12 micrometers

(B-5).

The energy that an infrared detector receives depends upon several factors. Most detectors determine the ratio of the energy emitted at a given wavelength from a material to that of a perfect radiator (called a black body) at the same temperature. This value is called emittance.

Emittance can be affected by the amount of energy the material reflects or allows to pass through or test surface geometry. A rough irregular object will normally have a higher emittance than a smooth object of the same material.

Reflected energy can be detected by infrared sensors causing inaccurate readings. High emittance materials are less affected by reflected signals due to higher energy values associated with these materials. If a material has a low emittance the surrounding background energy will offer greater interference. This disruptive energy must be compensated for to get accurate readings from the target material. Many systems use filters to select the optimum frequency to screen out intruding backgrounds. When inspecting a component made of varying materials with different emittance properties, the compensation procedure can be very complicated. Since most infrared monitors convert measurements directly into temperature readouts, collected data must be carefully analyzed for accuracy and consistency (B-5, I-1).

Thermography is a form of infrared monitoring that processes the detected energy into images. Many systems color code the images to indicate different

temperature zones. Thermographic photographs may be computer enhanced and offer an excellent permanent record for comparison to later measurements or trending.

Using the heat energy transmitted from a surface, contact detectors measure the temperature of a material directly. Fluid thermometers measure the expansion of the fluid from a reservoir into a calibrated tube. The amount of fluid that moves up the tube is dependent on fluid (usually mercury or alcohol) properties and target material characteristics.

Bimetallic thermometers use the fact that all metals expand at different rates under the same temperature gradient. These devices connect two different metals and are mechanically linked to a pointer. There is a graduated scale behind the indicator that indicates temperature based on the combined expansion of the two metals.

Resistance temperature detectors (RTDs) measure electrical resistance changes in conductors as a function of temperature. By knowing an experimentally determined relationship of resistance versus temperature, this device can indicate temperature. In many cases, the resistance reading is directly converted to a temperature readout.

There are many dyes that change color permanently after a certain temperature is exceeded. The dyes can indicate a wide range of temperatures and are available in paint, crayon or other coating forms. Some dye indicators can combine pigments to indicate a history of the materials temperatures (N-12, B-5, I-1).

4.2.12 Pressure Sensing

High accuracy pressure sensors, showing many improvements over conventional direct pressure sensors, are easy to calibrate accurately in place and respond closely to system pressure transients. Since their pressure is indicated by electrical signals, the measurements can be easily transmitted and recorded. The electrical nature of the signal makes it easier to process, enhance and combine with other monitoring devices.

By using an electrical potential across piezoelectric crystals, a sensor can determine pressure very accurately. This potential difference varies linearly with pressure changes experienced by the crystal.

Instantaneous and very accurate responses are offered by these devices. Experimental results indicate that they smoothly follow fluctuations in pressure. Being connected to an indicator by cables makes them easier to install and more accurate than devices that use a pressure tube. Pressure sensors may be calibrated in place without pressurizing the system or requiring additional test equipment. The compactness and easy signal routing of these devices make them suitable for locations that were previously difficult to monitor (N-12).

4.2.13 Position Sensing

Position sensing devices use sound, eddy currents, light, magnetic fields or mechanical probes to measure the relative position of component parts. Sound devices use a transmitter to originate the signal and a receiver to collect the signal. Distance or motion measurements are determined by time of travel

between transmitter and receiver. Most devices process signals and convert the results to a meaningful distance. These devices require a clear sound path without interference from deflecting surfaces to function accurately.

Eddy current probes use properties associated with the magnetic field of an alternating current to measure gap distances. Effects of the magnetic field of the eddy currents on the coil vary proportionally with gap separation. Changes in eddy current field properties can be converted to a gap distance.

Eddy current probes can be used to count shaft revolutions. By placing a notch on a rotating shaft, eddy currents are affected during each revolution. This notch effect can be converted to a revolutions per time output.

Photonic sensors use reflected light patterns to determine separation distance. Light sources project a narrow circular light beam onto the target surface and a detector senses the reflected light pattern. At a neutral position the sensor detects a full circle of reflected light. As the target moves away from this position, the sensor detects a different pattern of reflected light. Light pattern changes are directly proportional to the amount of target surface movement.

By measuring the rate of change of the reflected light pattern, sensors can detect target surface vibrations . Fiber optic transmission cables add flexibility and accuracy to these sensing devices.

Sensors can measure air gap distances by using basic capacitor properties. Two conductive plates, separated by a dielectric, form a capacitor. The amount

of current flowing across the plate is dependent on plate separation/size and dielectric properties. By designing component surfaces as conductor plates, air gap distances can be determined using capacitance current properties. The current varies inversely with the plate separation distance.

A magnetic flux sensor can be used to detect the distance to a permanent magnet. If the magnet is mounted on a target surface, the magnetic flux received by the sensor will indicate the distance to the target surface. Signal intensity and fluctuation can be correlated to target surface properties (N-12).

Mechanical probes can be used to measure surface separation distance. An example is the thrust collar position indicators used on many turbines. These devices are simple and easy to maintain. However, they are subject to inaccuracies due to wear from frequent use and inconsistent analyst operation.

4.2.14 Dew Point Measuring

Dew point monitors measure the moisture content of a compressed gas with respect to the content of saturated air at the same temperature. Hoses connected to the operating system transfer compressed gas via a regulator to sensing cells and electronic output modules.

A typical sensor consists of an oxidized strip of two metals that form electrodes with an outer and inner layer. As water vapor passes through the outer layer and deposits on the inner layer, electrode impedance changes. The amount of water passing to the inner layer is proportional to the vapor pressure

of the sample gas. Therefore, the bimetallic electrode impedance indicates sample gas water vapor pressure which is converted to moisture content in parts per million to determine the service condition of the sampled system (N-12).

4.2.15 Thermodynamic Analysis

Comparing actual system thermal output to design values can predict component problems. Computer models, using parameters sensed directly from the equipment, can use energy and mass balance relationships to evaluate the heat transfer and flow characteristics of a system.

The Navy has successfully developed this technique for distilling and air conditioning units. Laboratory test of these systems indicate results are very accurate. Other system tests, or even entire propulsion plant evaluations, are planned to further develop these procedures (S-9).

This analysis method is well suited for a "layered monitoring" approach. In the layered approach, an entire system is monitored using overall system parameters. As problems are indicated, the monitoring method scope is reduced, focusing upon isolated problems.

The entire secondary system of a plant can use the layered monitoring approach with thermal dynamic analysis. General parameters of the overall system (temperature, steam flow, pressure, etc.) may be easily monitored. Thermodynamic models can compare the actual thermal output for the entire system to design values. When actual global parameters deviate an unacceptable amount from design values, the analysis scope may be reduced to

smaller portions of the system or individual components. The analysis scope reduction continues until the problem or combinations of problems are identified.

An example scenario illustrates how the layered monitoring approach works. The scenario starts by analyzing the entire secondary system. Tests indicate the scope should be reduced to the steam turbines, then to the turbine condenser, then to the condenser circulating pump. Detailed analysis of the pump can identify a problem that was initially detected by the analysis of the total system.

Thermodynamic analysis methods require very accurate measurements of system temperature, pressure and flow which becomes vital for systems with a low thermal output. Such systems experience small heat fluxes, allowing inaccurate measurement of parameters to greatly affect thermodynamic inaccuracies.

4.2.16 Breakaway and Coast Down Analysis

Rotating machinery can be analyzed by evaluating the amount of force required to start equipment or the amount of time it takes for equipment to stop once the motive force is removed. This method of analysis can be used as a component global health indicator. If this method indicates a problem, other methods can localize problems.

Electrical equipment can be evaluated by analyzing startup current magnitude and waveform. Baseline data is established when equipment is new.

Changes in recorded data from these "normal" values indicate problems. The David Taylor Research Center (DTRC) has validated this process with several laboratory test (N-12, 15).

Startup current surge tests require a fast response ammeter. A means of recording the response will greatly assist the analyst and serve as permanent record for comparison with past and future data.

Breakaway analysis of a steam turbine uses turbine shell pressure, temperature and throttle position. When the turbine starts rolling a constant steam supply is applied and the time the turbine takes to get to normal speed is analyzed.

Breakaway testing can also be done manually. For small components (i.e. pumps), the operator turns the machine by hand. Larger components require the use of a strap wrench or other assist device. Operators use experience to determine if problems exist and if further evaluation by other methods is warranted. Since these methods are subject to interpretation by different operators, correlation between test data is difficult and problems are sometimes hard to identify.

Coast down tests measure the amount of time the machine takes to coast to a stop after the motive force has been removed. Baseline measurements are made with the equipment new to allow comparison to future measurements.

4.2.17 Actuation Time and Sequential Event Monitoring

Actuation or sequence time of a component or system can be used to indicate equipment condition. Trending of recorded data can assist the analysis process. Many factors may affect timed events requiring the analyst to use care in interpreting the results ensuring the correct degradation condition is identified.

Actuating switches or photocells must be accurately placed to properly represent timed sequences. Many events happen so quickly that they can not be accurately measured manually. Therefore, automatic devices like strip chart recorders or direct links to microprocessors must be used. The accuracy of these devices may have an effect on the validity of the recorded data. Automatic devices provided a permanent record of the data and assist trending with previously recorded data (N-12).

4.2.18 Trace Element Sensing

Trace element sensing systems introduce a trace element and monitor its movement within a component. These systems can indicate fluid system flowrate, leaks, or wear status. The use of trace elements for determining system flowrates was discussed in section 4.2.9.

Surface layer activation methods can indicate the amount of wear, erosion or corrosion of various systems. Sensors measure the gamma decay rate of a radionuclide on the surface and subsurface of the component. Component conditions can be predicted by measuring the radionuclide activity in debris collected downstream.

Other methods imbed radionuclides or chemicals within a components surface. As the overlaying material wears off, sensors can detect each tracer. By placing different tracers at different depths, an estimate of wear amount and rate can be made.

Tracer gases can be used to detect leaks across pressure boundaries like valves or heat exchanger tubes. A stable harmless gas (i.e. helium or other inert gas) is introduced on the high pressure side and a detector on the low pressure side senses the presence of the gas. By determining the low pressure side concentration change over a given time period, component leak rates may be estimated.

4.2.19 Online Chemistry Analysis

Several devices have been developed that indicate system chemistry conditions continuously. Some systems use conductivity cells to determine the concentration of ions in the system fluid. These cells monitor changes in electrical current between two electrodes that are emersed in the fluid. As the ion concentration changes, the electrode potential changes proportionally.

Conductivity cells are very sensitive to changes in temperature or system flow conditions. Temperature compensation can be conducted, but requires careful analysis procedures. Foreign materials in the fluid system may easily foul a cell causing faulty readings.

Conductivity cells serve as excellent early warning devices for systems cooled by salt water. Since the introduction of chloride ions will have an

immediate effect, alarms may be used to indicate a problem exists. Some work has been done in correlating conductivity to pH levels. However, these methods can be inaccurate and have not been widely proven.

Monitoring devices can determine the oxygen content of a fluid system, thereby indicating the corrosion potential. Many facilities introduce oxygen scavengers into sensitive systems to reduce oxygen levels. Oxygen monitors can determine the effectiveness of these scavenging agents.

4.2.20 Electrical System Analysis

Electrical system monitoring devices include current analysis, resistance measuring, surge voltage evaluating and fault identifying methods. Motor current analysis systems monitor the current characteristics of motors to detect problems. Electrical insulation wear or breakdown can be determined by resistance measuring devices. By applying a surge voltage and monitoring the response, equipment can determine electrical continuity. Sensors, using computer processing, can use electrical circuity signals to ensure the proper operation of breakers, relays and switches.

Motor current signature analysis (MCSA) methods monitor the electrical power supplied to a motor to analyze the mechanical work the motor performs. Some mechanical defects can be reflected in the time series and spectral components of the motor current. Monitoring the current drawn by MOVs can detect problems with gears, switches, spring packs or valve internals (N-12). Another MCSA method can detect broken rotors in induction motors (C-4).

The application of wide band instrumentation and signal processing, similar to that used by vibration analysis methods, further enhances MCSA. These methods may detect specific defects not indicated by only measuring the average power of the component. MCSA can be applied to power circuits with minimal impact making installation of devices on existing systems relatively easy (N-15, H-3).

Resistance measuring devices determine electrical insulation characteristics by applying a large voltage to the insulation. By measuring the current passing through the insulation and applying Ohmn's Law, resistance measurements are obtained and can be used to indicate an impending ground caused by foreign materials or insulation breakdown. Precautions must be observed to ensure the large voltages used by these devices do not damage the component being tested.

Surge voltage devices can detect grounds, phase to phase shorts or open circuits in electrical components. These devices apply a voltage pulse to two phases of a motor winding and compare current responses. By recording results on trace paper, fault analysis is enhanced and a permanent record is obtained.

Recently, some companies have developed sophisticated circuit analysis methods that can detect faults in circuit breakers, relays and switches. These systems model the systems with computer programs and compare system parameters (voltage, current, etc) to predicted values. Differences between predicted and actual values indicate a problem (D-2). The layered monitoring methods discussed in the thermodynamic analysis section (4.2.15) may apply to

these techniques.

4.3 Analysis of Data

There are several methods available to analyze data collected by the technologies discussed in this chapter. Pattern change analysis, correlation, comparison of data, and statistical analysis are some of these methods and have been alluded to in the previous sections.

Test results must be normalized to a common load condition to allow comparison of results taken under various component conditions. Normally, data is corrected to a value corresponding to design or 100 per cent load.

Pattern change analysis evaluates the pattern of the test data. Present analysis methods consider four types of change from a normal steady condition. These types of change are trends, steps, spikes and oscillation.

A trend represents a gradual change in magnitude of measured valves. This method requires evaluation of collected data over a period of time. No one data point is emphasized, rather the best-fit average of the data is transformed into a smooth curve. Upward or downward trends can indicate problems. This method may use alarms to signify when increased monitoring, scheduled maintenance or immediate corrective action is required.

A sustained step change in vibration levels can indicate a component problem. This method requires less historical data than trending, however, some time lag remains. There must be some previously taken data to establish that a step change in vibration level has occurred.

A spike represents a sharp change in vibration level that is short lived. Spike detections require little historical data making them a real-time fault detection method. Spike detections lend themselves to alarms through amplitude and duration settings.

Oscillation changes are marked by a change in vibration magnitude or the oscillation period. Little detailed work has been done on correlation of this feature to component fault modes (B-1).

Correlation methods combine data collected from several technologies. For example, acoustic monitoring of a pump may detect abnormal noise levels that show up in vibration and motor current analysis as improper signatures. The manner in which data from each technology combine can identify a specific problem. A group at the Massachusetts Institute of Technology (MIT) has developed relationships between correlated data and component modes of failure or degradation for facility transformers and other systems (N-12,H-4).

The comparison of data method evaluates component test information that is repeatable. This data may be presented in the form of curves or traces. Abnormal component conditions cause this data to shift from the normal presentation. Historical traces from known component failure modes can be used to determine the cause for component degradation.

Statistical analysis methods look for data instability or improper scatter and can successfully predict abnormal conditions even when test results are below alarm values. These methods establish an allowable deviation of data

from the norm. In addition, the pattern of component historical failures can be described mathematically and collected data points compared to identify problems. Fault trees may help determine the specific failed part.

Chapter Five

Application of Technology to Monitoring Needs

5.1 Introduction

This chapter concludes the process of identifying potential areas in which safety and performance of nuclear power plants may be improved. By comparing needs determined in Chapter 3 to applicable technologies identified in the survey of chapter 4, possible improvements to monitoring needs are determined. Many of the technological improvements that are proposed are developed completely, but not used by all commercial nuclear power plants. Other enhancements require minor changes for effective use, or need further research. Recommendations for technology research are summarized at the end of this chapter.

5.2 The Application of Technology

By summarizing the monitoring needs and technology categories in Table 5.2-1, each technology can be considered for potential need improvement.

Table 5.2-1

Monitoring Needs and Applicable Technologies

Monitoring Needs	Technologies
1. Oil analysis 2. Pump condition 3. Material internal 4. System health 5. Diesel air start/governor 6. Electrical fault identification 7. Operability verification 8. Battery condition 9. Steam generator internals 10. Reactor internal 11. Valve condition 12. Turbine condition 13. Integrated leak tests 14. RCP seal 15. Condensate/feed chemistry	1. Lubricant analysis 2. Eddy current analysis 3. Ultrasonic imaging 4. Radiography 5. Visual systems 6. Acoustic systems 7. Vibration analysis 8. Computerized data processing 9. Flow measuring 10. Stress, strain, torque measuring 11. Temperature sensing 12. Pressure sensing 13. Position sensing 14. Dew point measuring 15. Thermodynamic analysis 16. Breakaway/coast down analysis 17. Actuation time/sequential analysis 18. Trace element analysis 19. On-line chemistry analysis 20. Electrical circuit analysis

Table 5.2-2 summarizes the results of this evaluation. Other applications of technology may be possible. However, these applications may not be sufficiently developed for use in the near future and were not included in this thesis.

Table 5.2-2

<u>Summary of Technology Application</u>

Monitoring Needs	Technology
1. Oil Analysis	Lube analysis
	Sensing systems*
2. Pump condition monitoring	Lube analysis
	Imaging methods#
	Acoustic monitoring
	Vibration analysis
	Computerized data processing
	Sensing systems*
	Thermodynamic analysis
	Breakaway analysis
	Trace element monitoring
	Electrical analysis

3. Material internals	Eddy current Ultrasonic imaging Radiography Computerized processing Stress measuring Temperature sensing Pressure sensing Trace element analysis On-line chemistry
4. System health	Acoustic monitoring Vibration analysis Computerized processing Sensing systems* Thermodynamic analysis Breakaway analysis Event timing Electrical analysis
5. Diesel air start/governor	Imaging methods# Acoustic monitoring Vibration analysis Computerized processing

6 Electrical fault identification	Acoustic monitoring
	Computerized processing
	Temperature sensing
	Position sensing
	Event timing
	Electrical analysis
7. Operability verification	Imaging methods#
	Temperature sensing
	Trace element analysis
	Electrical analysis
8. Battery monitoring	Imaging methods#
	Temperature sensing
	Trace element analysis
	Electrical analysis
9. Steam generator internals	Eddy current
	Imaging methods#
	Acoustic monitoring
	Sensing systems $
	Stress measuring
	Thermodynamics
	Trace element analysis
	On-line chemistry analysis

10. Reactor vessel internals	Eddy current Imaging methods# Sensing systems $ Stress measuring Thermodynamics Trace element analysis
11. Valve condition	Eddy current Imaging methods# Acoustic monitoring sensing systems* Breakaway@ Thermodynamics Event timing Trace Element analysis On-line chemistry analysis Electrical circuit analysis

12. Turbine monitoring	Eddy current Imaging methods# Acoustic monitoring Vibration analysis Thermodynamics Breakaway analysis Trace element analysis On-line chemistry analysis Sensing systems*
13. Integrated leak tests	Eddy current Imaging methods# Acoustic monitoring Sensing systems*
14. RCP seal monitoring	Eddy current Imaging methods# Acoustic monitoring Sensing systems* Thermodynamics Trace element analysis
15. Condensate/feed chemistry	Flow measuring On-line chemistry analysis

Notes: * = Sensing systems include temperature, pressure, flow, and position sensing methods

= Imaging methods include ultrasonic, radiographic, and visual imaging methods

$ = Sensing methods in note * excluding position sensing

@ = A form of breakaway analysis involves monitoring the torque required to move a valve disk from its' shut or open seat

Table 5.2-2 represents an estimate of the best application of known technologies to the monitoring needs of the nuclear power industry to date. These needs are continuously changing and new technology advances are frequently introduced. As these changes occur, the table should be updated.

All of the technologies may use the analysis methods discussed in section 4.3. Comparison of data, pattern change analysis and statistical analysis apply to each technology used individually. Correlation can be used when data from the applicable technologies of a monitoring need are applied together. In the following discussions, examples of unique correlation methods and proven applications of technology will be given when appropriate.

Many technologies can be applied in the same fashion to several different monitoring needs. Common application technologies are, imaging methods (ultrasonic, radiographic or visual), vibration analysis, computerized data processing, sensing systems (temperature, flow, pressure, positions or dew point), breakaway analysis, actuation time, electrical circuit or on-line chemistry

analysis and thermodynamic examination.

Imaging methods can detect internal flaws within component materials or scan inside the component to determine if problems exists. These methods can be used in pump condition monitoring, diesel air start/governor monitoring, operability verification, battery monitoring, steam generator or reactor vessel internals inspecting, valve condition monitoring, turbine monitoring, integrated leak testing and RCP seal monitoring.

To predict component failure or degradation, vibration analysis can use abnormal shocks or vibrations from rotating, reciprocating or oscillating equipment. Application of this method can be used in monitoring pump conditions, system overall health, diesel air start or governor systems and steam turbines.

Human error can be reduced and data evaluation improved by adopting computerized data processing. Computers can collect, store and correlate data received from many monitoring methods which enhances the presentation of data collected allowing the broader and more accurate application of a technology. Due to the general nature of computer applications in component monitoring methods, computer data processing applies to every monitoring need.

Sensing systems which include temperature, pressure, position and dew point sensors can evaluate the basic operating parameters of a system. From this monitoring method, the operating status of components can be determined. Component parameters measured outside the normal or design range may indicate problems. Sensing systems apply to the following monitoring needs: oil

analysis, pump condition monitoring, system overall health monitoring, system operability verification, steam generator and reactor vessel internal monitoring, valve condition monitoring, integrated leak rate testing and RCP seal monitoring. As indicated by Table 5.2-2, several monitoring needs can be improved by only one or two of the sensing systems.

Required amounts of force necessary to start equipment, or the amount of time needed to stop the equipment once the motive force is removed, can be evaluated by breakaway and coast down analysis. Changes in these values can indicate component problems. Breakaway and coast down analysis can be used with pump condition monitoring, system overall health monitoring and turbine monitoring. A form of breakaway analysis can be used to monitor the torque required to move a valve disk from its' shut or open seat. "Running torque", used when the valve is shutting or opening, may also be used. Limiting torque values can be established to indicate when increased monitoring or repair is required.

Actuation or sequence time required for the completion of a system function can indicate component conditions and be used in system overall health monitoring, electrical fault identification and valve condition monitoring.

Current analysis, resistance measuring, surge voltage evaluating and circuit or component fault locating methods are included in electrical system monitoring. Conditions of an electrical system focus the efforts on specific problems. Pump condition monitoring, system overall health monitoring, electrical fault identification, operability verification, battery monitoring and

valve (MOV and SOV) monitoring can use these methods.

Many on-line chemistry analysis methods measure change in potential between two electrodes immersed in fluid of a monitored system. Electrical potential can indicate ion concentration, oxygen content or corrosion susceptibility of the system. Monitoring steam generator or reactor vessel internals, steam turbines and condensate/feed system components is possible with these devices.

Thermodynamic analysis methods use temperature, pressure and flow sensors to calculate the actual thermal energy in a system. Actual energy can be compared to the design value corresponding to the operating conditions. Differences between actual and design parameters can indicate system or component problems. Pump condition monitoring, overall system health sensing, steam generator or reactor vessel internal examining, valve condition monitoring, steam turbine monitoring, integrated leak rate testing and RCP seal inspecting can benefit from use of this technology.

Methods in which the remaining technologies are applied vary depending on the monitoring need they are applied to. Eddy current testing can be used to detect flaws or discontinuities in material internal examinations, to monitor steam generator or reactor vessel internal, to inspect steam turbines and to monitor RCP seal systems. Improper part locations in valve condition monitoring and integrated leak tests can be detected by the same technology.

Crack growth conditions in the internals of many materials can be determined by monitoring acoustic emissions from susceptible components.

Acoustic monitoring can be used as a system health indicator. Abnormal noises can be detected and the cause identified. This technique can be used in monitoring system health, diesel air start or governors, electrical faults (identified by pops or buzzing), and reactor vessel internals. Leaking steam generator tubes or valve seats and turbine imbalance or cracked blades can also be identified by this technology.

Trace element analysis can be used to indicate component wear or to detect system leaks. The wear indication process may be used in oil analysis, pump condition monitoring, material internal inspecting, steam generator or reactor vessel internal inspecting battery monitoring, steam turbine examining, and RCP seal monitoring. Leak detecting can be used in valve condition monitoring or integrated leak rate tests.

5.3 Recommended Technology Research

Many of the technologies discussed may be applied immediately to monitoring needs for improvements in nuclear power plant safety and performance, while other technologies require further research in order to utilize their full potential. Technologies that have vast potential after some work are: computer data processing, improved parameter (pressure, temperature and flow) sensing, acoustic monitoring, on-line chemistry and electrical circuit analysis. In addition, methods of further reducing sensor size and improving system operability verification should be pursued.

Improvements in every technology may result from further research in computer data processing, making this one of the most important research area

to pursue. One of the key issues is determining how to identify correct data. An example is eddy current testing. In this method flaws are normally detected solely by operator experience in determining the difference between flaw and noise signals. By programming sensors to act like trained experts (using artificial intelligence) the system can screen out unwanted signals and make sensor data easier to use. Other monitoring systems can show similar improvements by using this enhanced data processing.

A need for improved pressure, temperature, and flow sensors also exists. For many systems, these parameters do not vary over a large range. If the accuracy of the sensors is low, the collected data may not be very useful. Recent developments using glass fiber optics have shown a potential for improving sensor accuracy. A light beam is transferred through a glass sensor which alters the spectrum of the light dependent on the system pressure or temperature. Resolution of the spectrum is within a factor of one in 10,000 parts and the sensor response time is faster than current systems (N-16).

Acoustic monitoring methods that listen to the sound associated with a system need further development. Methods available that use an experienced operator data base to assist less experienced operators need further development. These processes train artificial analysis networks to analyze raw data in the same fashion that the experienced operator would.

Operators with many years of experience can tell when a system is not operating properly just because it does not "sound right." These operators have difficulty quantifying what the abnormal noises are, but years of hearing a

properly running machine allows them to detect a problem as soon as it is heard (N-17). Research should be conducted to identify the factors involved in this process and to determine how an automatic mechanical monitoring tool can be developed.

On-line chemistry methods have shown promise in identifying chemistry casualties like the introduction of chlorides due to salt water leaks. Recent studies have evaluated the use of the redox potential of a fluid to indicate system pH, ion concentration and oxygen or hydrogen content. These studies use electrode potential monitoring devices to measure system potential (B-6). Further development of these and other systems is important to the future of real time on-line monitoring of system chemistry.

Circuit analysis methods, discussed in section 4.2.20 (electrical system analysis), require further development to achieve their full potential. Development of computer programs to analyze the various parameters (current, voltage, resistance, etc) is needed. Better parameter sensors that may be easily installed in existing systems and that have sufficient accuracy are also required.

Smaller sensor research similar to that conducted for radiographic imagers (L-1) is needed for other systems. Many sensors are bulky and limited in use for systems that have restricted access which limits the monitoring capability of these techniques.

Proving the operability of a standby system is identified as important in Chapter 3. To date, little work has been done in this area. The key parameters of these systems must be identified and methods to predict how these parameters affect the system operability should be developed.

5.4 Chapter Summary

A summation of the possible ways of applying technology to the monitoring needs of the nuclear power industry and Table 5.2-2 posting the results of these findings are presented in this chapter. By pursuing the research recommendations of this section further technology applications may be developed. Although this survey is general in nature, covering all types of PWR plants, many specific design problems are addressed as well. As the needs of the industry and advances in technology change, the results identified should be reviewed and this evaluation updated.

Chapter Six

Summary, Conclusions and Recommendations

6.1 Summary

Improvements in the safety and performance of nuclear power plants must be made to maintain public confidence and ensure competitiveness with other power sources is enhanced. Table 6.1-1 outlines the process used by this thesis to identify potential improvement sources through the use of technology applications to service maintenance needs. The following discussion indicate the specific findings of each process step.

Table 6.1-1

Potential Safety and Performance Related Improvements Process

1. Determine basis for determining importance (impact on CDF or CFL)
2. Determine important events through industry survey
3. Identify important components (using #2 data)
4. Establish failure mode categories from the important components (using #3 data)
5. Develop monitoring needs from the failure modes (using #4 data)
6. Survey technology for improvements to the monitoring needs (focus on #5 needs)
7. Apply technology to the monitoring needs
8. Identify where further research is required

Industry studies indicating components with the largest impact on nuclear power plant safety and performance are used in this thesis. Selection of safety components is based on the potential to increase core damage frequency. Performance components were selected based on their effect on power plant capacity factor losses. Summaries of these findings are included in Tables 6.1-2 and 6.1-3

TABLE 6.1-2

Components with the Largest Safety Impact

Note: The associated important event from Table 2.2.2-1 is listed in parenthesis

1. Diesel generator (SBO)

2. Offsite power busswork (SBO)

3. Steam generator tubes (SGTR)

4. AFW piping, pumps, controllers and valves (Loss of AFW and SBO)

5. HPI piping, pumps, controllers and valves (loss of HPI)

6. LPI piping, pumps, controllers and valves (loss of LPI)

7. MFW piping, pumps, controllers and valves (loss of MFW)

8. CCW piping, pumps, controllers and valves (loss of CCW)

9. RHR piping, pumps, controllers and valves (loss of RHR)

10. Ventilation system piping, pumps, controllers and valves (loss of ventilation)

11. PORV (PORV failure and LOCA)

12. SGPORV (SGPORV failure and SB

13. Electrical switchboards (loss of vital power and SBO)

14. Primary system piping and valves (LOCAs)

15. Emergency batteries (SBO)

16. Reactor control systems (ATWS)

17. Reactivity control systems (ATWS)

18. RCP seals (SBO and LOCAs)

19. Main steam isolation valves (ATWS)

20. Reactor protection system (ATWS)

21. Turbine generator controls (ATWS)

Table 6.1-3

Components with Largest Impact on Capacity Factors

Note: Associated important events from Table 6.1-3 are in parenthesis

1. Steam generator tube rupture (same)*

2. Steam leaks through valves, flanges, etc (thermal efficiency)

3. Inefficiently operating auxiliary steam loads (thermal efficiency)

4. Leaking feedwater heater tubes (thermal efficiency)

5. Inefficient moisture separator (thermal efficiency)

6. Thermal shields (reactor vessel internals)

7. Core barrel flow channels (reactor vessel internals)

8. RCP seals (same)*

9. Turbine blades and rotors (same)*

10. Reactor coolant pumps and drives (same)*

11. Uninterrupted power supply (same)*

12. MFW piping (same)*

13. MFW pumps and drives (same)*

14. Leaking main condenser tubes (same)*

15. Control rod drives (same)*

16. Turbine EHC or overspeed (same)*

17. MFW chemistry (same)*

18. Circulating water system fouling (condenser tubes)

19. Fuel oil piping leaks (diesel generator)

20. Overspeed governors (diesel generator)

21. Various adverse conditions leading to excessive crankcase pressure (diesel generator)

22. Equipment associated with the integrated leakrate tests (same)*

Monitoring needs were identified by the important components. These needs were identified by using industry studies to determine component common failure or degradation modes. The monitoring needs are summarized in Table 6.1-4.

Table 6.1-4

Summary of Monitoring Needs

1. Oil analysis
2. Pump condition inspection
3. Piping, tube and vessel material internal inspection
4. System overall health inspection
5. Diesel air start and governor inspection
6. Electrical fault identification
7. System operability verification
8. Battery condition inspection
9. Steam generator internal inspection
10. Reactor internal inspection
11. Valve condition inspection
12. Turbine condition inspection
13. Integrated leak rate verification
14. Reactor coolant pump seal system inspection
15. Condensate and feed chemistry inspection

Literature and industry representative surveys were conducted to identify methods of improving the monitoring needs. This survey resulted in finding 20 applicable technologies that are listed in Table 6.1-5.

Table 6.1-5

Survey of Technologies

1 Lubricant analysis

2 Eddy current testing

3 Ultrasonic imaging

4 Radiography

5 Visual systems

6 Acoustic monitoring

7 Vibration analysis

8 Computerized data processing

9 Flow measuring

10 Stress, strain and torque measuring

11 Temperature sensing

12 Pressure sensing

13. Position sensing

14 Dew point measuring

15 Thermal dynamic analysis

16 Break away and coast down analysis

17 Actuation time and sequential event analysis

18 Trace element analysis

19 On-line chemistry analysis

20 Electrical circuit analysis

Monitoring needs were compared to the technologies surveyed. Technologies that may improve the monitoring needs were identified. Results of this analysis are summarized in Table 6.1-6.

Table 6.1-6

Summary of Technology Application

Monitoring Needs	Technology
1. Oil Analysis	Lube analysis Sensing systems*
2. Pump condition monitoring	Lube analysis Imaging methods# Acoustic monitoring Vibration analysis Computerized data processing Sensing systems* Thermodynamic analysis Breakaway analysis Trace element monitoring Electrical analysis

3. Material internals	Eddy current Ultrasonic imaging Radiography Computerized processing Stress measuring Temperature sensing Pressure sensing Trace element analysis On-line chemistry
4. System health	Acoustic monitoring Vibration analysis Computerized processing Sensing systems* Thermodynamic analysis Breakaway analysis Event timing Electrical analysis
5. Diesel air start/governor	Imaging methods# Acoustic monitoring Vibration analysis Computerized processing

6 Electrical fault identification	Acoustic monitoring Computerized processing Temperature sensing Position sensing Event timing Electrical analysis
7. Operability verification	Imaging methods# Temperature sensing Trace element analysis Electrical analysis
8. Battery monitoring	Imaging methods# Temperature sensing Trace element analysis Electrical analysis
9. Steam generator internals	Eddy current Imaging methods# Acoustic monitoring Sensing systems $ Stress measuring Thermodynamics Trace element analysis On-line chemistry analysis

10. Reactor vessel internals	Eddy current Imaging methods# Sensing systems $ Stress measuring Thermodynamics Trace element analysis
11. Valve condition	Eddy current Imaging methods# Acoustic monitoring sensing systems* Breakaway@ Thermodynamics Event timing Trace Element analysis On-line chemistry analysis Electrical circuit analysis

12. Turbine monitoring	Eddy current Imaging methods# Acoustic monitoring Vibration analysis Thermodynamics Breakaway analysis Trace element analysis On-line chemistry analysis Sensing systems*
13. Integrated leak tests	Eddy current Imaging methods# Acoustic monitoring Sensing systems*
14. RCP seal monitoring	Eddy current Imaging methods# Acoustic monitoring Sensing systems* Thermodynamics Trace element analysis
15. Condensate/feed chemistry	Flow measuring On-line chemistry analysis

Notes: * = Sensing systems include temperature, pressure, flow, and position sensing methods

= Imaging methods include ultrasonic, radiographic, and visual imaging methods

$ = Sensing methods in note * excluding position sensing

@ = A form of breakaway analysis involves monitoring the torque required to move a valve disk from its shut or open seat

6.2 Conclusions

Applications of technologies that offer potential improvements to the important safety and performance components are identified in this thesis. A process that may be used by any nuclear facility was used to identify improvement for the PWR industry. The study was kept general to ensure maximum applicability to all PWR designs.

The results of this study may be applied directly to the applicable components of a specific plant. By applying the process steps of Table 6.1-1 to the specific safety and performance related issues of a particular plant, further improvements may be gained. This method will allow plant managers to focus efforts where the greatest impact can be made for the least cost.

Using the recommendations proposed in this thesis, safety and performance related components may be improved. Due to changing plant designs and new technology research, this thesis should be updated on a frequent basis using the process outlined in Table 6.1-1. Further recommendations are included below.

6.3 Recommendations for Future Work

The following recommendations involve areas associated with this thesis that may warrant further research or modification of current practices:

1. Pursue the proposed research of section 5.3 (Recommended technology research).

2. Update the findings of this thesis as technology and the industry monitoring needs change.

3. Develop a more effective means of sharing information between the many organizations involved in new technology research. This will limit the amount of repetitive work and increase the effectiveness of research.

4. Further develop programs similar to the EPRI Center at Philadelphia Electric's Eddystone Station which quickly validates the feasibility of new monitoring methods. This contributes to the rapid transfer of new technology from the laboratory to practical application.

5. Utilize this process on one PWR plant as an example of how to best decrease plant capacity losses and reduce core damage probability for a certain cost expended. This may demonstrate the economics of the process described in this thesis.

6. Develop the optimum approach to incorporating new technology into a power plant maintenance program. One extreme waits to apply a technology until after it has been fully developed. Since many technologies may become obsolete, this method may use the new method for only a small portion of its

lifetime reducing the benefits. The other extreme applies the technology very early in the development stage. Since many technologies require several modifications to reach their full potential in actual power plant systems, this approach may result in substantial waste. A logical approach should be developed to optimize the useable life of a technology and reduce the cost of application.

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Appendix A

Definition of Abbreviations

ABT - Automatic bus transfer

AFW - Auxiliary feed water

ASP - Accident sequence precursor

ATWS - Anticipated transient without scram

CCW - Component cooling water

CDF - Core damage frequency

CFL - Capacity factor loss - a measure of the amount of energy lost due to an event compared to the amount of energy produced at full power.

CRDM - Control rod drive mechanism

EHC - Electrohydraulic control

EPRI - Electric Power Research Institute

HPI - High pressure injection

LERs - Licensee event report

LOCA - Loss of coolant accident

LPI - Low pressure injection

LWR - Light water reactor

MCSA - Motor current signature analysis

MFW - Main feed water

MOV - Motor operated valves

NDE - Non destructive evaluation

NRC - Nuclear Regulatory Commission

PLEX - Plant life extension

PLG - Pickard, Lowe, and Garrick, Inc

PORV - Power operated relief valve

PRA - Probabilistic risk assessments

PWR - Pressurized water reactor

RCM - Reliability centered maintenance

RCP - Reactor coolant pump

RHR - Residual heat removal

RPV - Reactor pressure vessel

RTD - Resistance temperature detector

SBO - Station black out

SCC - Stress corrosion cracking

SGPORV - Steam generator power operated relief valve

SGTR - Steam generator tube systems

SOV - Solenoid operator valve

UDRPS - Ultrasonic data recording and processing system

UPS - Uninterrupted power supply

Appendix B

Description of Important Events

Note: All events result in a loss of decay heat removal means and potential CDF increase.

1. Station black out (SBO) - initiates with a loss of offsite power following a reactor scram and emergency power sources (battery or diesel) expended or inoperative.

2. Loss of coolant accident (LOCA) - consists of several subcategories all resulting in loss of water from the primary system.

3. Steam generator tube rupture (SGTR) - tube rupture causes a primary to secondary leak requiring the steam generator to be shutdown and removing a decay heat disposal means.

4. Auxiliary feed water (AFW) failure - AFW inoperative on loss of main feed water flow causes a removal of decay heat disposal means similar to SGTR.

5. Anticipated transient without scram (ATWS) - a transient removing a decay heat disposal means (turbine trip or steam generator isolate) without a scram occurring. ATWS allows fission process to continue without heat being removed from the core.

6. High pressure injection (HPI) failure - results in loss of primary water inventory during a LOCA due to no makeup water available while the plant is still pressurized (greater than 1000 psig).

7. Low pressure injection (LRI) failure - same as HPI except occurs with the plant at atmospheric pressure.

8. Loss of component cooling water (CCW) - loss of cooling water to vital equipment causes component failure and removal of decay heat disposal means.

9. Residual heat removal (RHR) system failure - results in the loss of the only depressurized decay heat removal means.